## Highlight of the Issue

# Biological Solution to the Energy Crisis

*Lecture delivered on July 8, 2005 at Chiang Kai-Shek Memorial Hall, Taipei, Taiwan*

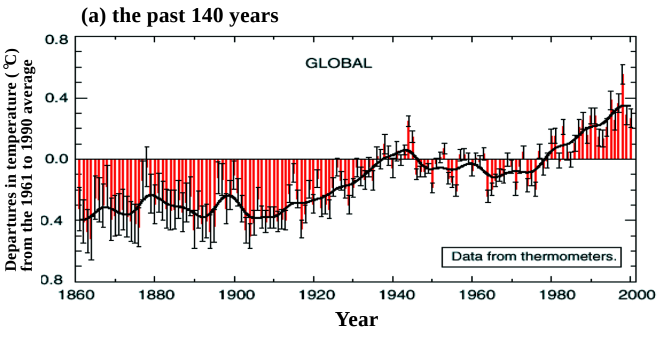
## Steven Chu

I am here to talk about the energy crisis and the areas of research that are taking place to solve this important problem. First, I am going to talk about the likelihood of global warming and suggest some possible solutions.

Shown in Fig. 1 is a plot of the average yearly temperatures of the earth over the past 140 years and the red bars indicate the yearly temperature deviation from the average. From this you will notice that since 1860, 19 of the 20 warmest years occurred since 1980 and 1998 was the warmest year on the records, and may be the warmest year in 1,000 years. However, 140 years is a short period on the geological time scale. Therefore, we need to look back a little bit further in time to see what the overall trend is. It is possible to do that by studying the ice samples, notably from the Antarctica. The red curves in Fig. 2 show the temperatures fluctuations in the Antarctica over the past 420,000 years. These temperatures are determined by measuring the difference in isotope content between $O_{16}$ and $O_{18}$ in the ice. It turns out that if the temperature is warmer, more of the heavier form of water evaporates and becomes accumulated in the Antarctica. In addition to the temperature data, the graph in Fig. 2 also plots the atmospheric concentration of both carbon dioxide and methane trapped in the glacier. Notice that these curves track each other beautifully. From this record, it's not really clear whether the greenhouse gases caused the temperature to rise or if the temperature rose followed by the increase in the greenhouse gases.

However, data over the last decade is beginning to indicate that over the last 50 thousand years, increase in greenhouse gases, especially methane, may occur prior to increase in temperature. Several other features are revealed by Fig. 2. First, the recent trend shows an 8℃ rise in temperature indicting that we may be in a state of potential global warming. However, note that humanity spent most of the time in the Ice Ages.

**Variations of the Earth's surface temperature for:**




140 year is nothing by geological time scales!

*Fig. 1: The average temperature of the earth over the last 140 years. 19 of the 20 warmest years since 1860 have occurred since the year 1980.*

Professor Steven Chu
Department of Physics & Applied Physics
Stanford University
Stanford, CA 94305-4060
and
Lawrence Berkeley National Laboratory
Berkeley, CA 94720
E-mail: schu@stanford.edu

**Temperature over the last 420,000 year**

**Soure: Working Group1 of the Intergovermental Panel on Climate Change**

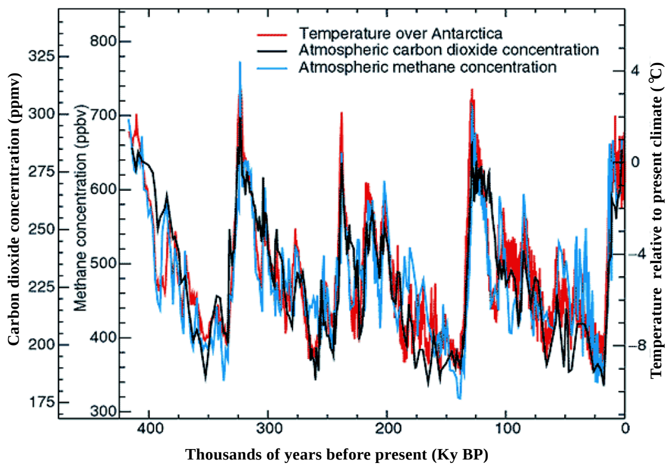



*Fig. 2: The red curves are the temperatures over Antarctica during the last 420,000 years. The temperatures are determined by looking at the oxygen-16 to oxygen-18 ratio in ice samples. The concentration of atmospheric methane and carbon dioxide tracks the temperature changes beautifully.*

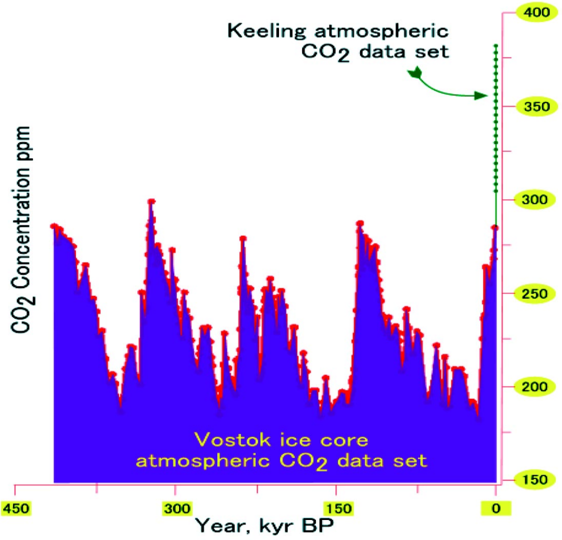



*Fig. 3: The concentration of atmospheric carbon dioxide in the last 420,000 years. The amount of greenhouse gas $CO_2$ has gone up and off the scale in the last 50 years.*

During such periods, regions such as the North America were largely covered by a permanent glacier. Therefore, why is everyone worried about global warming? Shouldn't we be worried about a new ice age? The reason we're worrying about global warming is that the amount of greenhouse gas $CO_2$ has gone up in the last 50 years and has gone off the scale, compared to the last half million years [Fig. 3]. Therefore, we are now facing a new problem. As the temperature fluctuates in the past, the $CO_2$ concentration was always at a lower level. The effect of the high $CO_2$ concentration we are facing is a serious concern. Therefore, the question is if we can predict climate changes due to an increase in greenhouse gases?

This reminds me of a great American philosopher of the 20th century, who happened to be a baseball player named Yogi Berra. He said many wise things. One thing he said was that predictions were hard to make, especially about the future. In order to have confidence about predicting the future is to predict the past. What does it mean to predict the past? We know the concentrations of common greenhouse gases over the past 1,000 years [Fig. 4]. Notice the concentrations of the greenhouse gases were fairly flat until 1750, the beginning of industrial revolution. With the onset of the industrial revolution, we started to burn coal, oil and gas. With the consumption of fossil fuels and the rapid increase of world's population, there is a corresponding increase in the amount of $CO_2$, methane and $N_2O$.

If one uses the best computer models available for temperature prediction, one finds that the variations of the model parameters that account for natural phenomena, such as volcanoes and solar variations, cannot account for the temperature variations [Fig. 5]. However, the same model, accounting for

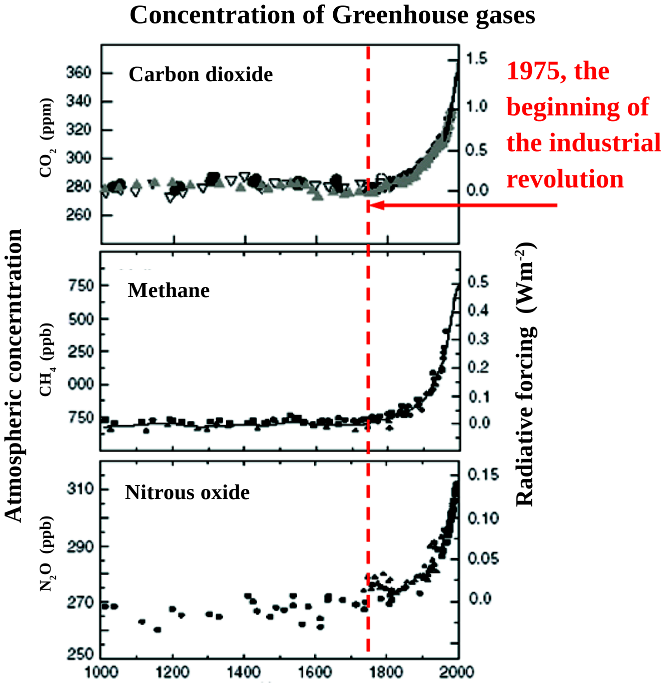



*Fig. 4: The concentration of greenhouse gases over the last 1,000 years has remained fairly flat until the industrial revolution, when the burning of coal, oil, and gas has gone up.*

the effects of atmospheric green house gases, can yield reasonably good agreement between temperature variations and the corresponding changes in green house gas concentrations.

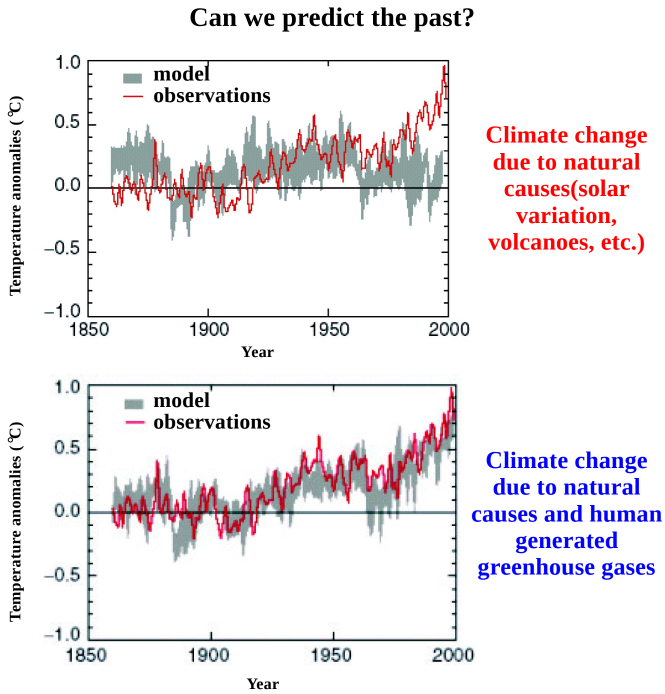



*Fig. 5: The best current computer model cannot accurately predict the temperature without taken into account the effects of the greenhouse gases. The same computer model with the effects of the green house gas added gives a much better prediction for the temperature variation.*

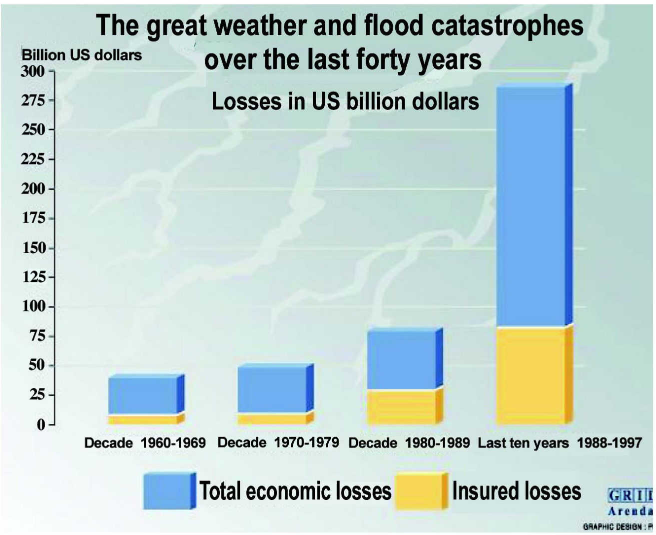



*Fig. 6: Plot of the great weather and flood catastrophes over the last 40 years. A large rise in the number of storms and the amount of property damage and insurance losses is seen over the recent years.*

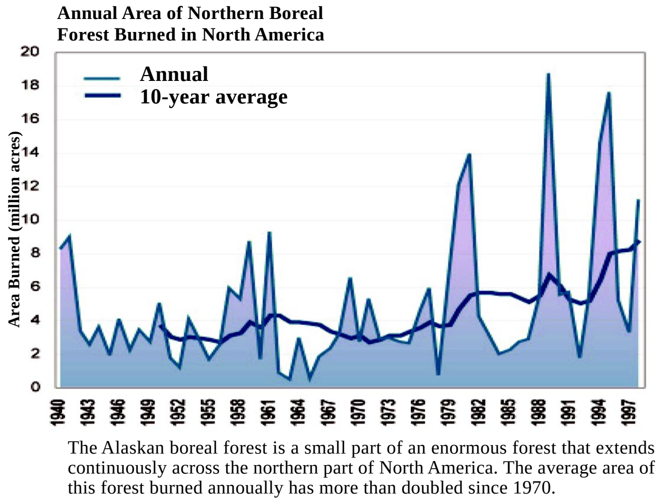



*Fig. 7: Global warming also results in the increasing frequency of forest fires in North America. Shown is area of Northern Boreal forest burned annually.*

This does not mean that the increase in green house gases caused the temperature rise. However, as we make further progress, the models become more robust, and the most likely cause of the rise in temperature is due to the fact that after the industrial revolution, greenhouse gases are generated and released into the atmosphere.

What will happen to the atmospheric $CO_2$ concentration if $CO_2$ emissions are reduced by a factor of 20 over the next 100 years? Unfortunately $CO_2$ is a very stable gas. Once it is generated, it stays there and cycles between the atmosphere and the ocean. In other words, the $CO_2$ concentration will stabilize for at least another 100 to 300 years. If the $CO_2$ concentration in the atmosphere is stable for such a long period of time, what will happen to the temperature? The temperature will continue to rise. In fact, there is a large time lag between the effects of increasing green house gas concentrations and the corresponding rise in temperatures.

With the rise in temperature, sea levels will rise due to the increase of water from ice being melted in Antarctica and Greenland. Why does climate matter? Well, climate is really the average and the extremes of many phenomena, including the hot and cold, wet and dry, snow packing, snow melting, winds, and ocean currents. The consequences of many of these phenomena remain unknowns, especially the effects of ocean currents. Specifically, we do not have an understanding for how a temperature rise will affect the current flow. For example, if the Gulf Stream which travels from the Carribean to the North Atlantic changes directions and moves southward towards Africa, Northern Europe, which is at the same latitude as mid Canada, will become a frozen tundra. Due to the enhanced evaporation and precipitation which accompany the rising temperature, it has also been predicted that global warming will also increase the occurrences of storms, floods, and wild fires. There will be property losses due to sea level rises. In addition, the productivity of farms and fishers will be greatly affected. The livability of cities in the summer will also change. Finally, the distribution of species and patterns of diseases will be altered.

To illustrate the damages caused by adverse weather changes, Fig. 6 shows the major weather and flood catastrophes over the last 40 years. The data shows a rise in the number of storms and a rise in the amount of property damage and insurance losses. This has become such an important issue that many of the insurance companies for hurricanes and flood are beginning to raise their rates in a dramatic fashion. An adverse change of global warming is the increasing frequency of forest fires in North America [Fig. 7]. It is also anticipated that the average mortality rate for people living in large cities in the United States will also increase by 2020-2050 [Fig. 8].

The results from the computer models show that it's not only the average temperature of the Earth that is affected. Regional temperatures are also affected by global warming. The computer models suggest that most of the temperature increases will occur over land. Depending on whether the $CO_2$ concentration will be increased by a factor of 2 or 4 over the pre-industrial level, the extent of temperature increase will also be different and the predictions of temperature increase by the computer model for the two cases are shown in Fig. 9. For comparison, Fig. 3 shows that the pre-industrial level of atmospheric $CO_2$ concentration to be 275 parts per million (ppm), and at the present, the atmospheric $CO_2$ concentration is already above 375 ppm. The simulated results at four times the

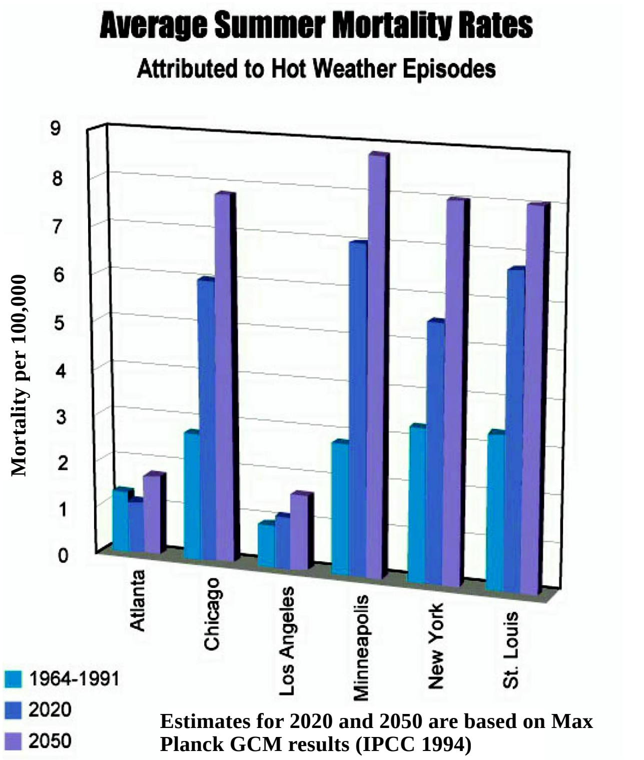



*Fig. 8: The average mortality rate due to hot weather for people living in big cities in the USA. It's predicted that by 2020-2050, mortality rates will increase.*

pre-industrial $CO_2$ concentration indicate that the temperature of mid-western part of the United States, one of the most productive areas of agriculture in the world, is to rise by 4-5 degrees Celsius. That will turn the Mid-West into a dessert. In Glacier National Park, glaciers have all but disappeared since 1910, so there is a proposed name change of the park to Non-Glacier National Park.

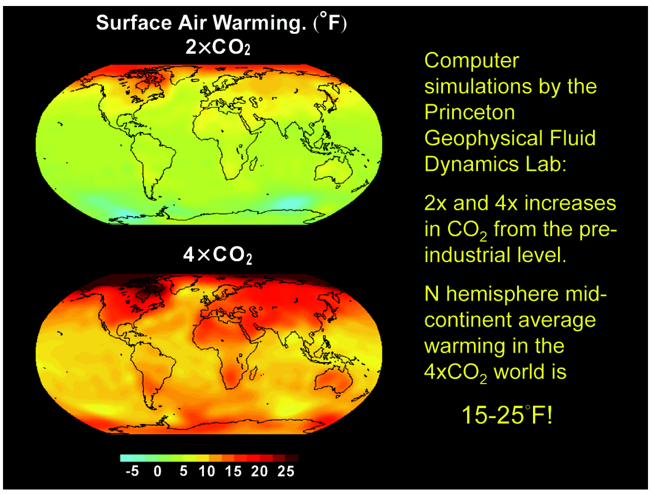



*Fig. 9: Computer models prediction of the temperature over Earth for the cases where $CO_2$ increased by 2 times or 4 times since the pre-industrial level. Note that most of the predicted temperature increase is over the land.*

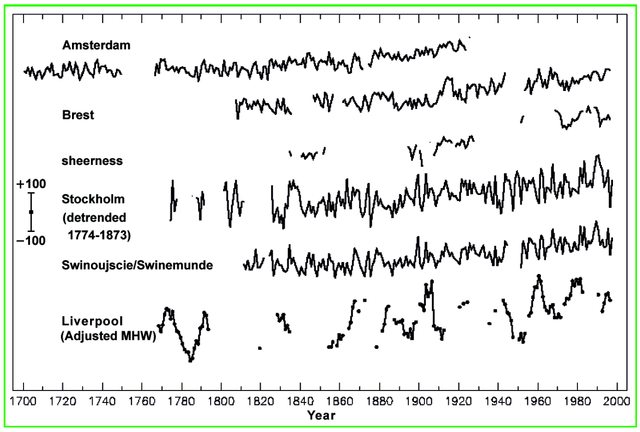



Figure 6: Time-series of sea level for the past 300 years from Northn Europe: Amesterdam, Northerlands; Brest, France; Sheerness, UK; Stockholm, Sweden (detrended over the period 1774 to 1873 to remove to first order the contribution of post-glacial rebound); Swinoujscie, Poland (formerly Swinemunde, Germany); and Liverpool, UK. Data for the latter are of "Adjusted Mean High Water" rather than Mean Sea Level and include a nodal (18.6 year) term. The social bar indicates ± 100 mm. [Based on Figure 11.7]

*Fig. 10: Direct sea level rise measurements in Amsterdam, Stockholm, and Liverpool. Note that there is a general trend of sea level rising over the past 150 years*

At the present, great ice packs are breaking up. An example is the Larson Ice pack of Antarctica which broke off in 2002. The melting of ice packs, especially those located on land masses such as Greenland and the continental shelf of Antarctica, will cause a rise in the sea level. Direct measurements of sea levels in Amsterdam, Stockholm, and Liverpool, show that there is a general trend of sea level rising over the past 150 years [Fig. 10]. Here's an investment tip: if the sea level rises 1 meter, all the regions marked in red in southern Florida, including Cape Canaveral will be under water [Fig.11]. Therefore if one were to buy land next to the red regions in Fig. 11, one will be acquiring beach front property. The situation will be much worse in Bangladesh, where a 1 meter rise will affect the life styles of hundreds of millions of people. The increase in water temperature will also kill the

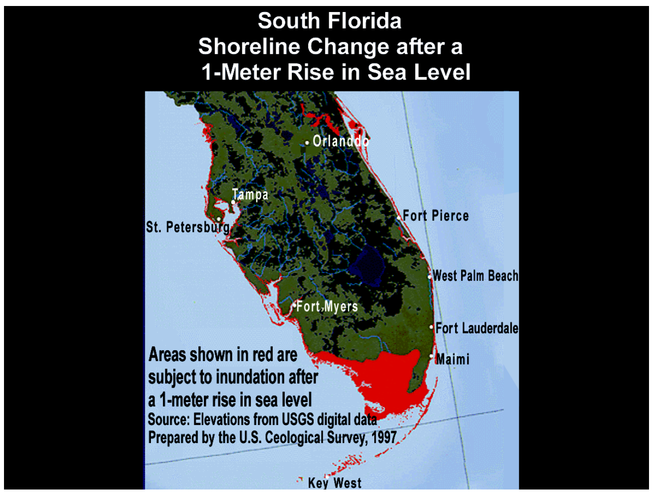



*Fig. 11: The area in southern Florida that would be inundated if the sea level rises 1 meter.*

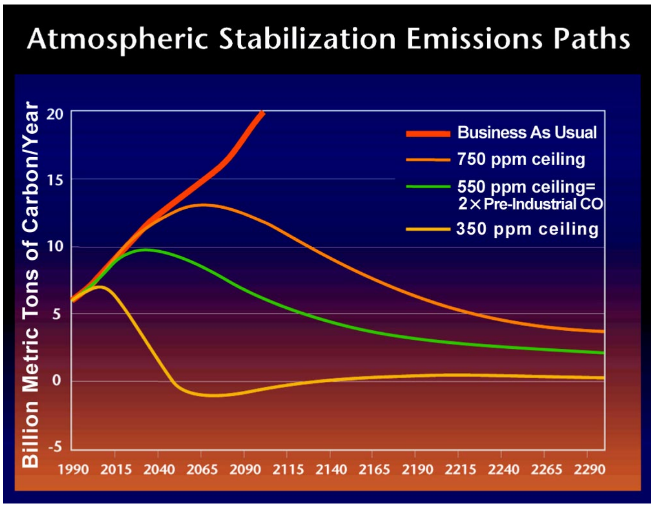



*Fig. 12: The amount of atmospheric $CO_2$ based on different emission patterns. The condition will continue to get much worse if we do not change the current pattern of $CO_2$ production.*

living organisms within the coral, and leaving behind a white skeleton. The red curve in Fig. 12 shows that the atmospheric emissions will become much worse, if the current trend continues. An approach to alleviate global warming is to cap the $CO_2$ concentration at 550 ppm.

The scope of the energy crisis can be better understood if one examines the trend of the world demand of energy resources. As shown in Fig. 13, between 1971 and 2000, the total use of energy has doubled and is expected to triple by 2020. Most of what we use now is oil and gas, followed by coal. The rest of the energy sources we use contribute to a very small amount of the total energy consumption. In 1959, a geophysicist named King Hubbert predicted that the 48 states of the US would have a peak in oil production in 1970. This

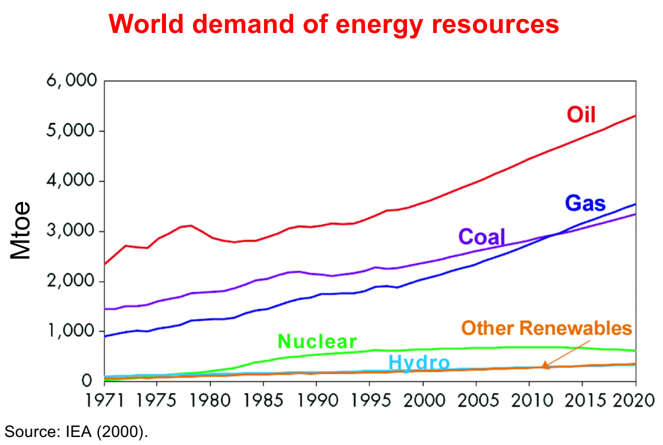



*Fig. 13: The world demand of energy resources. Between 1971 and 2000, the total use of energy has doubled. It's expected to triple by 2020.*

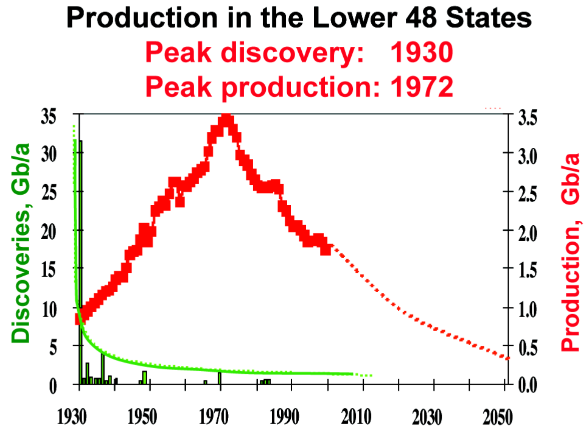



*Fig. 14: The production of oil in the lower 48 states in the US. The red curve is the production and the green curve shows the discoveries.*

concept was regarded as heretical and he was laughed off the stage in 1959. In fact, he was wrong. The peak occurred in 1972. As Fig. 14 shows the peak oil production in the lower 48 states, and the oil finds in Alaska did not affect domestic oil production significantly. Fig. 14 also shows that we are running out of places to find oil in the US, and that we have well passed the production peak. In summary, we are essentially running out of oil in the United States.

You have to make a guess, as to what the world's total reserves are. The best guess by the United States Global Survey (USGS), and the Department of Energy (D.O.E) is the best estimates of total discovered and undiscovered global reserves. Their generous estimates state that we have not yet discovered 2/3 of the oil. Based on factors such as the increase of and different assumptions on the rate of oil consumption, their predictions of peak oil production are anywhere between 10-30 years from now. Some predictions state that we are at the peak of oil production, but other predictions state that the oil production peak will be at 2040. However, most predicts that the oil production peak will occur at around 2015-2030. Once the oil and gas production has peaked, there will be somewhat of an ensuing panic, and the price of oil may become 60 dollars a barrel, and we will be at the beginning of the end.

First, we will run out of oil. Then we will run out of gas. So what's left? There will still be a lot of coal, hundreds of years of it. It is estimated between the years 2003-2030, the total power output of coal plants will be 1.4 TW, or $1.4\times10^{12}$ watts of power. The United States now consumes 0.3 TW of power. With the new coal plants that will be built, the projection is that in the next 30 years, we will add 3 times more $CO_2$ to the atmosphere than from the previous 250 years. If we continue with business as usual, and continue to use fossil fuel, we will have bought into a really serious problem. Once you spent tens and hundreds billions of dollars on coal burning plants, it will be tough not to use them. There is also energy available from tar sands and shell oil which, like coal, are actually considered to be reserves as well. However, these energy sources are equally bad for $CO_2$ emissions. Remember, the feeling now among many scientists is that we may not have ten or twenty years left to get the energy situation under control.

The situation is analogous to the following scenario: we are all on a little island and there is no escape out of the island. There is a volcano on the top of the island, and there is lava oozing down and the lava is oozing such that it's going to cover the entire island. In fact that is why the island is there, because of the lava. You can well imagine that the lava will then ooze down and consume the village, consume everybody on the island, and everything will be dead. The village elders have some concerns, so they have a meeting to discuss the situation. Let's pretend we are eavesdropping at this meeting. The first thing, one of the village elders may say is "Well, our political system can't deal with this problem, because this is a 50 or 500 years problem. We are not really sure but in any case we only work on a 2 or 4 year cycle. So let's forget about it." Another islander may say "Since we don't know whether it is a 50 or 500 years old problem, shouldn't we wait to be sure before we start to think about what to do?" Finally, the third islander may say "We are very clever people. Yes, we don't know how to divert the lava flow, but maybe when the lava gets near, we will think of something." In actual fact, I don't think anybody on this island would be saying those things. The reason they won't be saying this is because the lave flow looks very visible. Therefore, every morning they get up they can look at the lava flow. Running out of oil and global warming are less visible. However, global warming is quickly becoming more visible. In just the last decade or so, it has become quite visible in terms of the pictures I've just shown you. What about energy conservation and efficiency? Some people think that will solve the problem. It won't solve the problem, unless we stop consuming energy at a level beyond a factor of 10. We think energy efficiency and conservation can reduce energy consumption by as much as a factor of 5, but the final problem remains: we have got to stop the $CO_2$ emissions.

What are some possible solutions when fossil fuels run out? With nuclear fusion one can burn hydrogen to acquire a lot of energy and relative to fission, the fusion solution is an environmentally clean solution. However, after 60 years of research we are not yet close. The most optimistic researchers predict that maybe in 40 or 50 years, commercial energy sources based on nuclear fusion may become possible. At the present, nuclear fusion remains a research program. We should continue to do research in fusion, but we can not put all our eggs in one basket.

An alternative energy solution is nuclear fission. However, it has three problems. First, nuclear fission produces a lot of radioactive waste. In addition, there is always the concern of nuclear proliferation. The third issue is the emotional aversion the public may have towards nuclear fission. If the United States wants to get itself on a nuclear economy, it will have to make nuclear power reactors capable of producing 3 TW of power. This is equivalent to one new billion watts (GW) reactor every week for the next 50 years. As a result, the amount of the radioactive waste generated will become significant. Specifically, there is the problem of radioactive waste with the isotopes that are made in nuclear reactors. Fig. 15 shows the types and amount of isotopes that are made in nuclear reactors and the times required for them to decay. The pink line shows the current E.P.A. standard for what the United States considered to be safe. It would take more than 100,000 years for all isotopes to fall below the E.P.A standard. Roughly speaking, the nuclear waste problem is a 100,000 years problem and 100,000 years is a long time. Civilization is only 8,000 years old. The Neanderthal men just appeared on earth about 100,000 years ago. Therefore, the waste problem will leave quite a legacy for future generations.

There is hope in that we can recycle the radioactive fuels and research on how to efficiently convert long lived nuclear waste into shorter lived radioactive isotopes. In principle, the amount of waste reduction can be as much as a factor of a hundred and with the waste having considerably shorter life time. However, we do not quite know how to resolve the waste problem in a very efficient way. I think a lot of research should be done on this problem, because nuclear energy, either fusion or fission is $CO_2$ neutral.

What is left is energy from the sun. When you think of solar energy, you normally think of photo-voltaic cells. The trouble

**Waste production of plutonium, minor actinides, long-lived fission products**

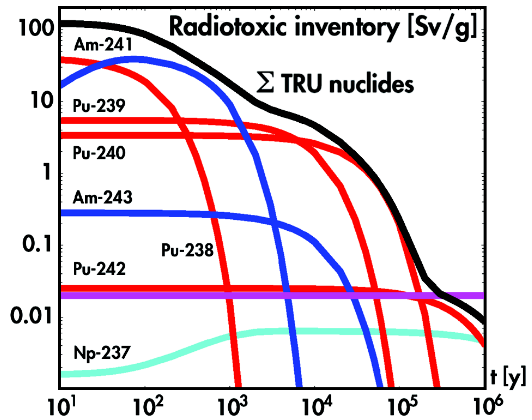



*Fig. 15: The production of radioactive wastes has a function of time in years. The purple line shows the current E.P.A. standard for what the US considers safe.*

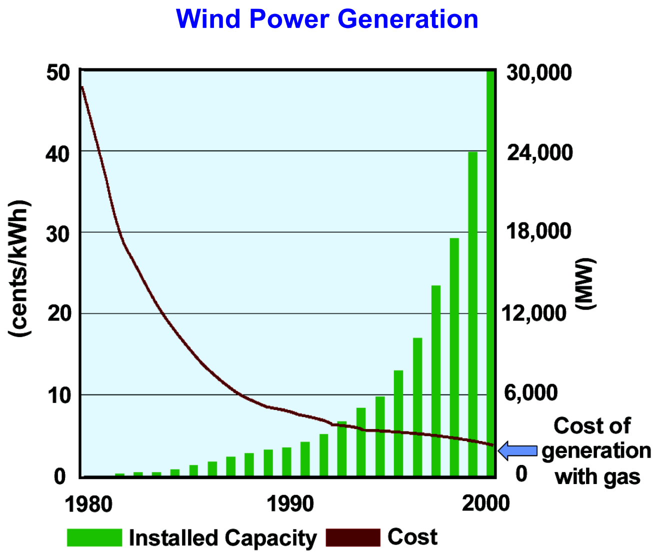



*Fig. 16: The red curve shows the cost of generating electricity with wind, and the green bars show the installed capacity of production due to wind. The arrow shows the cost of generating electricity with gas.*

with photo-voltaic cells is the economical cost associated with this technology. In order to become competitive with coal, gas, oil, and nuclear energy, the cost associated with photo-voltaic cells needs to be brought down by at least a factor of five, perhaps by a factor of ten. More research on how to make photo-voltaic cells more efficient should be done. Solar energy also causes wind, and wind power is a promising and much cheaper source of energy. As an energy source, wind has made incredible technical progress. Fig. 16 shows that over the years from the 1980's to 2000, the cost of generating energy from wind has plummeted. The green bars show the installed capacity due to the drop in cost. For comparison, the arrow on the same graph indicates the cost of generating electricity with gas. Wind, properly utilized, can provide 10-20% of our electrical need. However, wind energy can not quite be considered as a power-on-demand source. If the wind does not blow, there is no electricity. The problem with both solar and wind produced energy is that one still need to convert the electricity into stored energy, so the energy can be available on demand. One possibility is to use hydro-electric means for energy storage. What that would involve is that as electricity is generated, it is used to pump water uphill. When electricity is needed, all one needs to do is to let the water flow down. There are plans to store energy this way, especially with nuclear reactors, because the nuclear reactors run day and night. This idea would involve pumping the water at night, when the load is low. However, the problem is that there is not enough water in the world to do this.

Instead, we would like to convert solar energy into electricity, and then into chemical fuel. It is easy to convert electricity into chemical fuel. We know this from our grade school days. By putting the correct electrodes in water and turning on the electricity, you can break down water into hydrogen and oxygen. When hydrogen is burned, it becomes water which is a very clean end product. Therefore, converting sunlight to electricity to generate hydrogen seems very clean. However, the conversion of electricity to hydrogen would lose a factor of five in energy content. Therefore, a ten-fold increase in the demand of solar electricity would become fifty times more expensive. What we need to do is to perform research on how to convert electricity into chemical fuel. It is considerably cheaper than electrolysis.

Finally, there is photosynthesis. Nature, over the last couple of billion years, has found a way to convert sunlight, $CO_2$, water, and some nutrients into chemical energy. Fig. 17 outlines this remarkable process. The light go into some molecule on the leaf, the energy hops around and finally deposits into the reaction center, and there the energy from the sun is made into a chemical bond that can be burned for chemical fuel. We are beginning to understand this process, and as we understand this process, it appears increasingly more difficult to artificially mimic this system in the next 10-20 years. We know how to absorb light and separate the charges. That process is what photo cells do. We also know how to transfer these charges, by molecular transport. It is the chemical conversion of these separated charges into the chemical bonds that is extremely hard. The most difficult part about this process occurs during the process when a molecule or a small group of molecule holds several electron volts of energy. In this state, the molecules

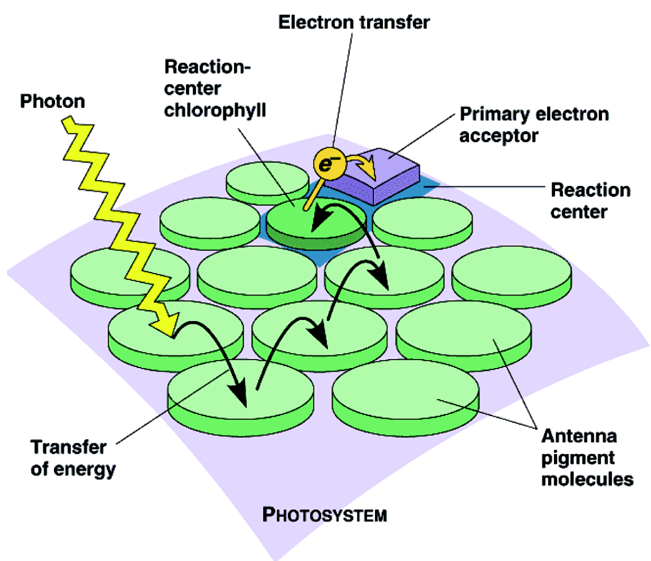



*Fig. 17: The photosynthesis process of converting sunlight, $CO_2$, water and some nutrients into chemical energy. The light will go into some molecule on the leaf, the energy hops around and finally deposits into the reaction center.*

tend to blow up after a few million to billion cycles. The result is that the photochemical process will last for a day or a week at the most. This is true of plants: they blow up. However, nature has found a way around this problem. As the molecule that processes the energy into chemical fuel blows up, there is another molecule that comes in and replaces the broken unit so the process can continue. Until we develop nanotechnology that senses and self repairs the broken energy conversion unit, using an artificial technology for energy production will remain to be a problem. This issue is universally true for organic materials. Inorganic material can last for decades under the hot Sun, but organic materials do not last very long.

Given that we are probably not going to have the solution in terms of nanotechnology and a mixture of inorganic and organic nanotechnology within the next ten or twenty years, we can turn back to nature and try to convert sunlight, $CO_2$, $H_2O$ and nutrients to biomass and then to a form of the chemical energy we like (ethanol, methanol, methane or possibly hydrogen). In going from sunlight, $CO_2$, $H_2O$, and nutrients to biomass we can make vast improvements in the current existing plants. We can genetically modify plants such that they generate their own fertilizers. We used to rotate crops, so that plants that are fertilizer intensive, such as cotton or corn, would be planted on one year followed by growing a plant that puts the nitrogen back in the soil the next year. Now we use oil to turn it into ammonia to make fertilizers. However, remember that oil is going to run out. We can genetically modify plants to be self-fertilizing such they need very little water, grow very fast, and are naturally resistant to pest. Corn is one crop that US is growing and the US is subsidizing its farmers $1-3 billion a year. What one needs to do is to convert corn to corn oil and then convert corn oil into bio fuel.

The problem with corn is that if you look at how much energy one needs to invest to grow one unit of energy of ethanol, approximately two units of energy are needed. It's a good idea for corn farmers, because they get subsidized, but it is not a good deal for the world. In addition, the amount of $CO_2$ emission associated with corn production is substantial [Fig. 18]. Sugar cane in Brazil is one crop that has financially broken even. The sugarcanes can be fermented to create ethanol. Flex-cars, which have engines that switch back and forth between burning ethanol and gasoline, are now being used more and more. Right now 20% of the automobile fleet is composed of the flex-cars, and it is predicted in the next couple of year, the ratio of flex-cars can increase to 80%. At the current price of 60 dollars a barrel, its cost a factor of two less to run car on ethanol. This is a good approach for Brazil, because Brazil has lots of water and three growing seasons. However, it may not work for the United States and Europe.

Switchgrass is another crop being investigated at as well. It is essentially a weed and composed mostly of cellulose. A key feature of this crop is that it grows very fast and does not require much water. Therefore, people are looking into whether it is possible to mutate switchgrass in a fruitful way so as to improve the way we convert cellulose into chemical fuel. The current method uses a lot of hot acid and produces a lot of $CO_2$ in the process of converting the cellulose into ethanol. We know that over the last couple of billion years, nature has developed a way to convert cellulose or bio-waste into fuels like methane gas. Fig. 19 is a picture of the bacteria that does this. It is possible that we can study how these bacteria achieve such conversion, and improve the efficiency of such processes. We can do so by changing the bacteria's genome in a dramatic way. There are also bacteria in the stomach of cows and termites. They have the means of converting cellulose to chemi-

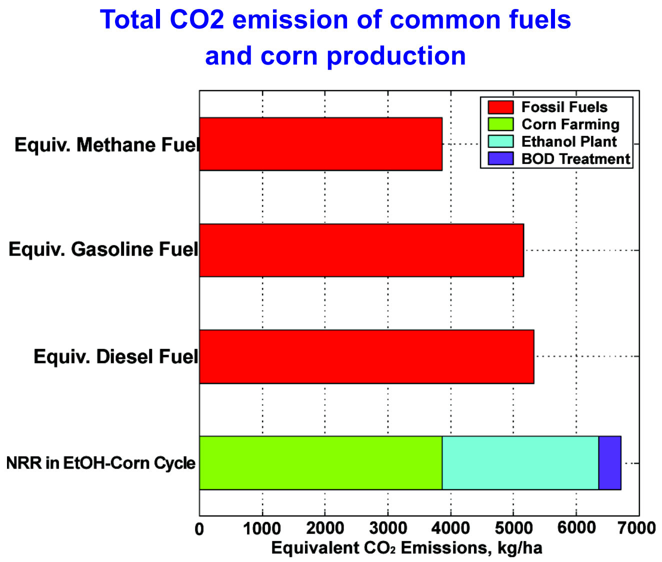



*Fig. 18: The total $CO_2$ emissions of common fuels and corn production.*

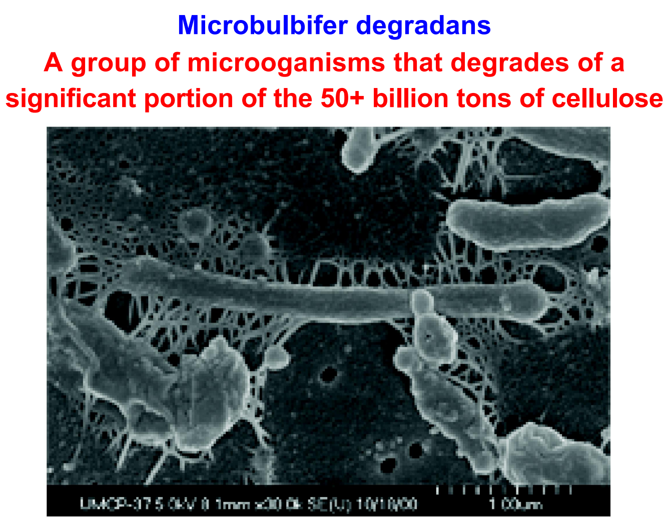



*Fig. 19: Picture of the bacteria that can convert cellulose or bio-waste into fuels like methane gas.*

cal energy that they can use. If we are fed a lot of cellulose, it just passes through our digestive system. We don't extract much energy from it at all. However, for termites, all they do is eating cellulose.

There is a more aggressive approach called synthetic biology. A potential application of this approach is in drug discovery. Instead of telling an organism to take 1 or 2 proteins to create a drug, one can be more ambitious and make the organism to grow many proteins in a little organic, synthetic factory. An example is the synthesis of the anti-malarial drug of artiminsinin. It has been found that one can extract a chemical compound out of the plant A. annua found in Southeast Asia to be used effectively against malaria. Malaria is a very serious disease and it kills approximately two million people a year. The known medicines to combat malaria are quinine based drugs, but the protozoa that causes malaria has developed a resistance to these quinine based drugs. Unless we find a drug to combat malaria, the disease is going to kill a lot more than two million people a year. Although artiminsinin is very effective, it is very costly to produce using this plant. What Jay Keasling has done is to figure out the pathway that the plant makes the artiminsinin, and he just incorporates this pathway into a bacterium, such that it making a dozen or so genes that form the compound. This is called synthetic biology. It is a natural extension of recombinant DNA. Now we can ask if the same approach can be used to make methanol, ethanol or methane from cellulose more efficiently? In fact, we have a project that has been going on in which one takes these micro-organisms and study their genome such as to determine a pathway which lead to the digestion of the cellulose and convert it to hydrogen. However, hydrogen is not our favorite fuel, so we prefer to make ethanol or methanol. The question is: Whether can we modify the existing plants or organisms or design new ones that can directly produce energy by photosynthesis? This is yet another scientific challenge that has some hope. However, the first order of business is to mutate a standard plant, convert it into biomass, and improve the conversion of biomass into chemical energy. Remember, we already have proof of this concept in Brazil, where sugarcane is being modified into direct energy. If the efficiency of this process is improved by a factor of three, this approach can be pursued in the U.S. as well. There is enough arable land in the U.S. such that we can supply all the petroleum needs for the U.S. There is enough extra land that can be dedicated towards growing plants to create energy.

The point to take away from this is that a diversified portfolio of investments are needed to develop numerous sources of new energy, whether it is in fusion, fission, electrochemistry, solar cell efficiencies, or biological approaches. I personally think that the first solution that might be practical probably lies at the interface of biology and the physical sciences at the nano-scale.

What are the U.S. and the international countries concerns? They are all worried about their national security, which is being tied to their energy security. The U.S. has developed a foreign policy that allows them access to oil. It's also not a secret that China, as its economy continues to grow rapidly, that it too is positioning itself to have access to oil. India is following them as well. A potential conflict is building up, when there isn't enough oil to go around and countries will do anything to supply themselves.

Energy is also intimately tied to economic prosperity. If the price of energy dramatically goes up, it would really put a dent on the world economy and lifestyles can dramatically change. If all the natural energy reserves on land, namely coal, tar sand, and oil, are used up over the next 400 years, huge damage will be done to the environment. These are the things that people in the world should be paying attention to. In my mind, it is the single most serious problem we are facing today that science has to solve. If we don't solve this, the life style of the world will change dramatically. If we don't find a cure to heart disease, stroke, or cancer, the life style of the world won't change. Life will go on as we know it. The sustainable $CO_2$ neutral energy source, however, is a global problem.

Should we start a Manhattan Project to solve the energy problem? I think "Yes" we should and the world should. However, it's little different, because when the United States started the Manhattan Project during World War II, we knew about nuclear fission and chain reactions. So a lot of basic science was actually done. Therefore, we need a Manhattan Project for the energy crisis before we discover chain reaction, and we better start it in the next couple decades. How do you go about doing something like this? The answer may be found in history. The Bell Laboratories was a place I spent nine years of my life. It was a remarkable industrial lab for about eighty years. You might think the invention of the transistor at the Bell Lab was done by a small group of people, namely Bardeen, Brittain, and Shockley who shared the Nobel Prize for the invention of the transistor. In fact, there were teams of people working on that project. Bell Laboratory decided they would like to invent a low power solid state switch to replace the vacuum tubes as switches, because they knew there were reliability problems associated with vacuum tubes.

When they decided to "invent" the transistor, they did not have the necessary material science to grow germanium and silicon with high enough purity. They did not know about the basic physics of electrons in semiconductors and how impurity affects them. They didn't know about surface states on semiconductors. And they didn't know a lot of the details of the p-n junctions. In fact, they had to solve all of these

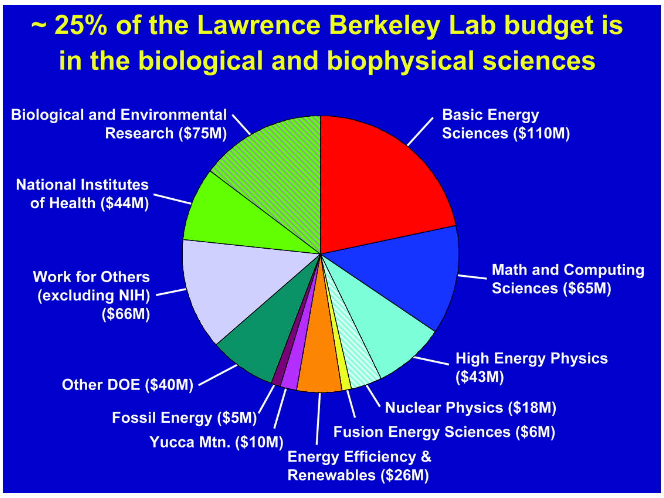



*Fig. 20: The distribution of Lawrence Livermore Laboratory budget. Note that about 25% of the budget goes into the biological and biophysical sciences.*

problems. These problems could not have been solved by professors at research universities in the same time frame that Bell Lab did it. It would have taken a decade or two for professors one by one, publishing papers, and going to conferences. Bell Lab can throw a kitchen sink at it and get it done in maybe a half dozen years, and that is what they did.

This brings me to why I left a very rich school, Stanford University to go to a not-so-rich public school, University of California, Berkeley. And also why I decided to leave my laboratory to run the Lawrence Livermore National Laboratory, where I have to administer. Believe it or not, I actually have to worry about electricity and plumbing. It is a half a billion dollar a year laboratory, located next to the Berkeley campus, with all unclassified research work. It is a very distinguished laboratory. Of the fourteen Nobel Prize winners who are faculty member at UC Berkeley, ten of them were or are employees at the Lawrence Berkeley National Lab.

The character of Lawrence Berkeley Lab has changed. It started out in high energy physics, nuclear physics, and chemistry, but only a small part in those areas remains [Fig. 20]. That's not to say that there are not a lot of distinguished work being done in those areas. In fact, there is another Nobel Prize winner waiting in the wings, for the discoveries made in high energy physics, but roughly a quarter of the lab now does biology or biophysics. We run the largest non-classified D.O.E. super computer in the country. We also run the most efficient genome sequencing facility in the country. It is a very multipurpose laboratory. Because we are leaders in nanoscience, physics, chemistry, life science, computational science, and material science, the Laboratory really has a lot of the parts that can address the question I have been talking about. This is one of the primary reasons why I took this job. I have been the director of Lawrence Berkeley National Laboratory for almost a year. The day I walked in the door, I started talking about the energy problem. During that time, I think people have become increasingly excited and compelled that they should be working on this problem. As the director, I don't order them to work on the energy problem. What I can do is to get them excited about the problem. At the discretionary level, I can fuel little projects. On the flip side, I can go to the Department of Energy, to Congress, and tell them of the need to do this. I am very optimistic that something will happen.

In summary, scientists are continuing to make better predictions to global warming. We really have to create solutions to this energy crisis and try to convince our world leaders to take immediate actions. Limiting the amount of $CO_2$ emission and investing heavily into research are both needed to solve this important issue. As new technology can one day brings us the needed solutions, the polar ice caps will continue to melt.